

DIFFUSION LENGTH MEASUREMENTS IN SOLAR CELLS - AN ANALYSIS AND COMPARISON OF TECHNIQUES*

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SUMMARY

A brief review of the major techniques for measuring minority carrier diffusion lengths in solar cells is given. Emphasis is placed on comparing limits of applicability for each method, especially as applied to silicon cells or to gallium arsenide cells, including the effects of radiation damage.

INTRODUCTION

In this paper we are undertaking a big topic, and have had to limit the number of techniques studied in-depth. In all cases we have put numbers into equations appearing in references in order to determine limits of applicability of various methods. Parameters are: material type (direct gap or indirect gap, usually GaAs or Si), range of values found in the literature for diffusion lengths including radiation damage values, doping density, optical absorption coefficient, recombination velocity, and cell dimensions. Some of our conclusions are expressions of opinion, and we welcome open discussion. A bibliography is given in the appendix.

A limited number of reviews or comparisons are in the literature. For example, Runyan's book Semiconductor Measurements and Instrumentation has a chapter on lifetime, including references. The American Society for Testing and Materials has a book Lifetime Factors in Silicon, and a publication "Minority Carrier Diffusion Length in Silicon by Measurement of Steady-State Surface Photovoltage". Reynolds and Meulenberg (1974) compared four techniques. K. O. Leedy has collected "A Bibliography on Electron Beam Induced Current Analysis of Semiconductor Devices" (1977).

We begin our analysis of minority carrier diffusion length determinations by writing down the familiar diffusion equation, assuming minority electrons are being generated in a p-type solar cell base:

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$$D_n \frac{d^2 \delta n_p}{dX^2} - \frac{\delta n_p}{\tau_n} + G_n(X) = 0 \quad (1)$$

where D_n is the diffusion coefficient, τ_n the minority carrier lifetime, $G_n(x)$ the generation rate, and δn_p the density of generated excess minority electrons. The general solution is

$$\delta n_p = A \cosh \frac{X}{L_n} + B \sinh \frac{X}{L_n} - f(G_n(X)), \quad (2)$$

where f is some function, and $L_n = \sqrt{D_n \tau_n}$ is the minority carrier diffusion length.

UNIFORM GENERATION

The simplest application of equations (1) and (2) is when $G_n(x) = \text{constant}$ (uniform generation). If $\delta n_p = 0$ at the solar cell junction depletion region edge, and the surface away from the junction is described by a surface recombination velocity, then the short circuit current, J_{sc} , is a simple function of diffusion length. In the case of a perfectly efficient BSF the recombination velocity is zero, and if the cell thickness is large compared with L_n ,

$$J_{sc} = q G_n L_n. \quad (3)$$

The point to make concerning uniform generation techniques is that the relationship between current and diffusion length is generally straight forward. However, making an accurate measurement of the generation rate is more difficult. If cell geometry remains nearly the same for all cells investigated then the technique is quite useful, especially for comparative purposes. These measurements have been done using γ -rays, X-rays, and particle beams (See bibliography attached).

ELECTRON BEAM INDUCED CURRENTS

Solutions to equation (1) are more complicated when absorption depends on position. A popular technique for determining L , especially in direct gap materials is the so called EBIC technique. There are a large number of papers in this area, and for the bibliography we have selected ones that best helped us to understand fundamentals and delineate major conclusion.

In the early 1970's Hackett made a detailed analysis of electron beam excited minority carrier diffusion profiles in semiconductors. He assumed the electron beam was an ideal steady state point source

located a distance ξ beneath the semiconductor surface having a characteristic recombination velocity s . In Hackett's analysis a normalized recombination velocity $S=s/(L_b/\tau_b)$ is defined, where L_b and τ_b are diffusion length and lifetime respectively. Jastrezewski, Lagowski, and Gatos used Hackett's results to show that

$$\Delta p(\xi) = (GL_b^2/D) \left\{ 1 - [S/(S + 1)]e^{-\xi/L_b} \right\}, \quad (4)$$

where L_b is the "bulk" diffusion length (our ultimately desired L) uninfluenced by effects of surface recombination at the surface through which the beam is passing. An L_{eff} is defined as the "apparent L " observed, as is influenced by recombination. L_{eff} is determined by measuring currents, I , generated at a junction a distance X from the electron beam, and

$$I = I_0 e^{-X/L_{eff}}. \quad (5)$$

In this geometry, X and ξ are perpendicular to each other. By Eqn. (4) and a simple argument one gets

$$\frac{L_{eff}}{L_b} = \left\{ 1 - [S/(S + 1)]e^{-\xi/L_b} \right\}^{1/2}. \quad (6)$$

This is an important equation, and is plotted in Figure 1. Thus when $S = 0$, $L_{eff} = L_b$, always. If $S = \infty$, $S/(S + 1) = 1$ and $L_{eff} = L_b$, when ξ is several times larger than L_b . Intermediate cases are shown in Figure 1. ξ can be controlled by varying the electron beam energy, and this is plotted in Figure 2 for silicon and gallium arsenide. Thus, for a given energy, the electron beam penetrates considerably deeper in silicon than in gallium arsenide. Note that

$$\ln \left(1 - (L_{eff}^2/L_b^2) \right) = \ln (S/S + 1) - \xi/L_b. \quad (7)$$

So a plot of the left hand side vs. ξ gives S from the intercept and L_b from the slope. This is not as simple as it looks. To make the plot, guesses for L_b are made until a self consistent straight line plot is found. Also, S is the normalized parameter.

To better define the situation Watanabe, Actor, and Gatos showed that the true recombination velocity s can be determined from

$$s = D \left[\frac{\partial}{\partial \xi} \ln I \right]_{\xi = 0}, \quad (8)$$

where D is the diffusion coefficient. (On the basis of this they made spatial profiles of s over the surface of a representative silicon sample.) The above analysis demonstrates that bulk diffusion lengths can be determined by EBIC even when surface recombination influences experimental results.

In all measurement techniques considered in this paper, measurement of L becomes more difficult when L is comparable to material or device dimensions. This is often the situation for solar cell designs. The problem was addressed by Flat and Milnes in 1978 for the EBIC technique, and Von Roos also determined that measurements of L were especially difficult when L is comparable to or greater than layer thickness.

Thus EBIC is a very powerful and fundamental tool for determining L, but the user should be aware of the potential complications. To completely avoid surface recombination effects, Figure 1 shows that $\xi \sim 2.5 L_b$ is needed, which implies that L_b should be less than about 20 μm for silicon, and less than about 8 μm for gallium arsenide. $L < 8 \mu\text{m}$ is often the case for gallium arsenide, but 20 μm is a rather short diffusion length even in irradiated silicon. Thus to measure L using EBIC in silicon probably requires use of the analysis associated with equations (4) through (8). Even for materials with short diffusion lengths one should use structures whose dimensions are large compared with diffusion lengths.

SCHOTTKY BARRIER PHOTOCURRENT

In this technique a Schottky barrier solar cell is made on the material of interest. Monochromatic light is shined on the cell, and the cell can be reverse biased. If the cell thickness is much larger than the diffusion length, then the short circuit current is given by:

$$J(\lambda) \sim \left(1 - \frac{e^{-\alpha W}}{1 + \alpha L} \right) \quad (9)$$

where α is the optical absorption coefficient and W the depletion layer width. If experiments are done with no bias, then $W = W_0$.

Thus

$$\frac{J(\lambda)}{J_0(\lambda)} = \frac{1 + \alpha L - e^{-\alpha W}}{1 + \alpha L - e^{-\alpha W_0}} \equiv J \text{ normalized} \quad (10)$$

A plot of J_{norm} vs. αW gives a series of curves dependent on αL . Thus a comparison of calculated and measured J_{norm} vs. αW yields αL , and L, if α is known.

We have analyzed expected results from this type experiment for both silicon and gallium arsenide, and Table I shows our results.

Doping densities of 10^{14} to $10^{18}/\text{cm}^3$ are assumed. For a density of 10^{14} per cm^3 depletion widths are from $W_0 = 5 \mu\text{m}$ to $W = 10 \mu\text{m}$ at high reverse bias. For silicon and gallium arsenide the range of absorption coefficients vs. wavelength is reasonably well known. (If α is not well known spectroscopic ellipsometry is a non-destructive, accurate method to measure α). In Table I we have assumed that the experimenter can set the monochromator to get α near 200 cm^{-1} , 10^3 cm^{-1} or 10^5 cm^{-1} . Absorption edges in direct gap materials are so sharp near the band edge that getting 200 cm^{-1} may be difficult. For silicon this value is reasonable. In any case, the value of L for making $\alpha L = 1$ for each case is listed in the table. αW_0 is the simple product. Calculated sensitivities, using Eqn. 10 are given. Since we feel that $\sim 10\%$ sensitivity is needed, the range of L for which this technique is applicable is given in the table. For comparison, the last column gives the experimentally observed ranges found in silicon and gallium arsenide, including radiation damage values. We conclude that this technique is generally good for direct gap materials but will work only for very lightly doped silicon, and even then only marginally. Two words of caution: In direct gap materials α changes so rapidly with λ that great care should be taken to measure α at the wavelength of interest. Note that α is temperature and impurity sensitive near the band edge. Secondly, the width W is often measured by capacitance voltage plots. Since materials other than silicon have high interface state densities, charges in these states shift C-V curves and give erroneous values for W .

SURFACE PHOTOVOLTAGE

In this technique light of wavelength just above the band edge strikes the surface of the semiconductor exciting electron hole pairs. Because the surface is a "sink" for recombination, a potential gradient is created relative to the back surface of the material. Generally this voltage is detected capacitively (an ac coupling) by chopping the light beam at roughly 10 Hz. Measurements of the intensity necessary to make the surface photovoltage constant are made as a function of wavelength. Plots of this intensity are made vs. α^{-1} and the intercept of the zero intensity is the diffusion length. The technique was shown by Wang et al to work for pn junctions (under specified conditions), and by Stokes and Chu for solar cell short circuit currents.

The conditions for reliable use are as follows:

- (1) $\alpha d_1 \ll 1$ i.e. absorpt. in the emitter (or surface depl. reg.) is small.
- (2) $d \gg L$ i.e. the cell is thick compared to L ,
- (3) $p \gg \Delta n$ i.e. low level injection,
- (4) $d_1 \ll L$ i.e. the emitter is thin,
- (5) $\alpha d > 1$ i.e. most light is absorbed in the base,

where $\alpha = \alpha(\lambda)$ is the optical absorption coefficient, d_1 the emitter thickness for a cell geometry or surface depletion thickness in bulk material, d the total cell thickness, and L the diffusion length. To meet condition (1), α is made low by choosing λ near the band edge. Condition (2) is often the most difficult to meet for common solar cell designs. Philips showed that this condition could be relaxed, but Chu and Stokes found poor agreement if $d \sim L$. (3) is met by choosing reasonable light intensity. For most cells, $d_1 \ll L$ by deliberate design. Finally, $\alpha d > 1$ is easy to satisfy because the base of cells are often thick enough to absorb most of the light, and because α can be controlled by wavelength selection. The above statements are true for silicon cells, gallium arsenide cells, and recently for amorphous silicon cells where diffusion lengths of only a few hundred angstroms can be found. As a practical rule of thumb, the shortest diffusion length measurable is about $\frac{1}{4}$ of the $(1/\alpha)$ value at the highest α needed to make the measurement. For example, in a - Si $\alpha = 10^5 \text{ cm}^{-1}$ at 2.5 e.v. photon energies. Thus $\frac{1}{4} \times 10^{-5} \text{ cm} = 250 \text{ \AA}$! In GaAs the minimum L measurable is about 0.1 \mu m for $\alpha_{\text{max}} \sim 2 \times 10^4 \text{ cm}^{-1}$.

FINAL STATEMENTS

All techniques have the limitation that semiconductor thicknesses should be large in comparison with diffusion lengths, in order to simplify interpretation. This is often violated in solar cell designs. Each of the techniques discussed have advantages and disadvantages which must be considered. We feel it is important that the limits of applicability of particular methods be realized.

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Table I - Schottky Barrier Photocurrent Technique

| Doping Density | Depletion Region Width | | Assumed Absorption Coeff., α | L to make $\alpha L = 1$ | αW_0 | Sensitivity $\frac{\Delta J}{J}$, % | Measurable Range of L | Observed Ranges of L |
|--|------------------------|------------------|-------------------------------------|--------------------------|--------------|--------------------------------------|------------------------------|---|
| | W_0 (zero bias) | W (with bias) | | | | | | |
| $10^{14}/\text{cm}^3$ ($> 100 \Omega\text{cm}$ in Si) | 5 μm | 10 μm | 200 cm^{-1} | 50 μm | 0.1 | 8% | 5 to 30 μm | 20 to 500 μm in Si (2 to 100* in GaAs) |
| | | | 10^3 | 10 | 0.5 | 17 | | |
| | | | 10^4 | 1 | 1.5 | 10 | | |
| $10^{16}/\text{cm}^3$ (1 Ωcm Si 2 Ωcm GaAs) | 0.5 μm | 1 μm | 200 cm^{-1} | 50 μm | 0.01 | 1% | 0.3 to 2 μm | 10 to 300 μm in Si 0.5 to 3 μm in GaAs |
| | | | 10^3 | 10 | 0.05 | 4 | | |
| | | | 10^4 | 1 | 0.50 | 17 | | |
| | | | 3×10^4 | 0.3 | 1.5 | 10 | | |
| $10^{18}/\text{cm}^3$ ($< 0.1 \Omega\text{cm}$ Si 0.3 Ωcm GaAs) | 0.1 | 0.3 | 200 cm^{-1} | 50 μm | 0.002 | $<< 1\%$ | $\leq 1 \mu\text{m}$ only | 3 to 30 μm in Si 0.2 to 2 μm in GaAs |
| | | | 10^3 | 10 | 0.01 | 1 | | |
| | | | 10^4 | 1 | 0.1 | 8 | | |
| | | | 5×10^4 | 0.2 | 0.5 | 17 | | |

*Diffusion lengths this large in GaAs are quite rare: See Nelson's papers.

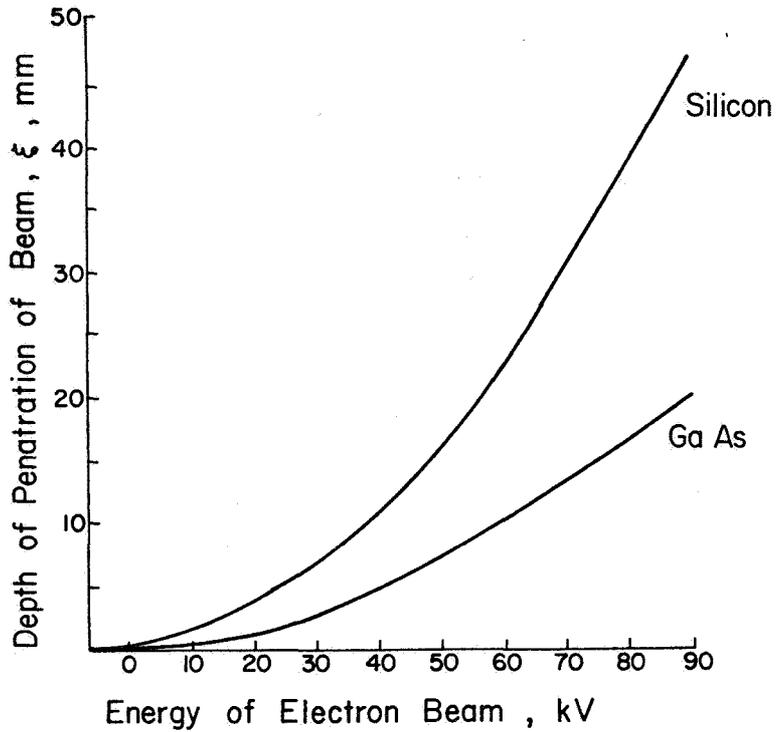


Fig. 1: Normalized diffusion length L_e/L_b vs. normalized depth ξ/L_b , for various values of normalized surface recombination velocity.

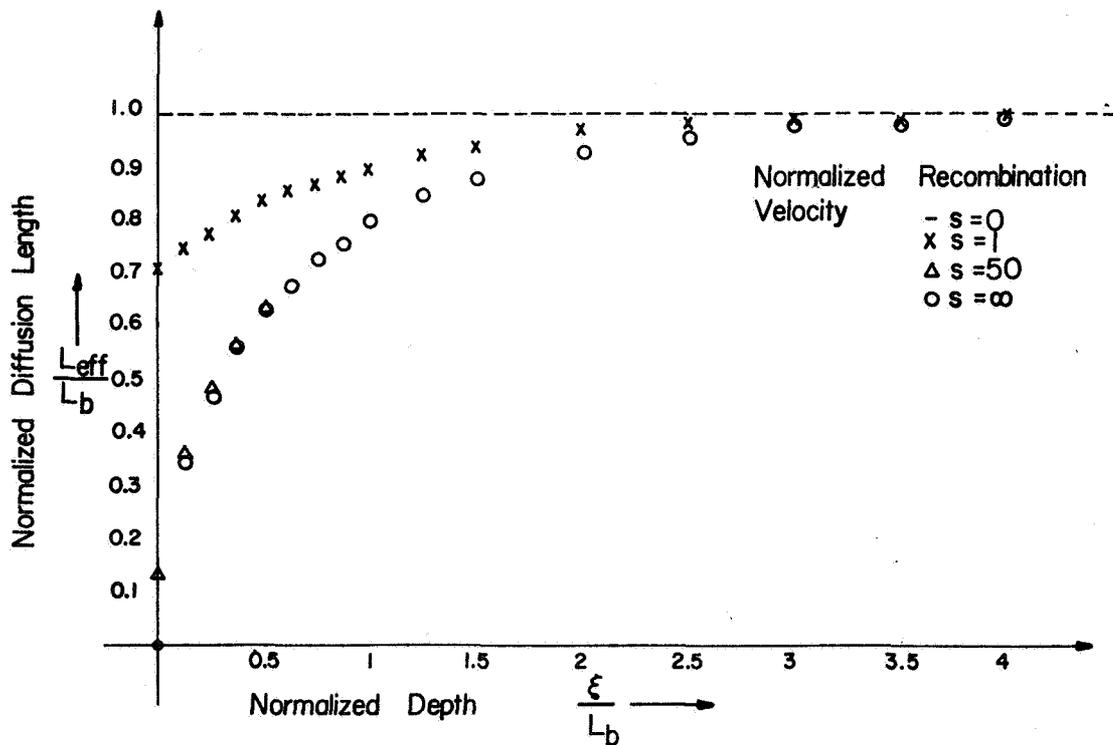


Fig. 2: Electron beam penetration depth as a function of beam energy for Si and GaAs.